Automatica 81 (2017) 209–216

Contents lists available at ScienceDirect

Automatica

journal homepage: www.elsevier.com/locate/automatica

Brief paper

Error-dependent data scheduling in resource-aware multi-loop networked control systems☆

Mohammad Hossein Mamduhi [a,1], Adam Molin [b], Domagoj Tolić [c], Sandra Hirche [a]

[a] Chair of Information-oriented Control, Technical University of Munich, Arcisstraße 21, D-80290 München, Germany

[b] ACCESS Linnaeus Centre, KTH Royal Institute of Technology, SE-100 44 Stockholm, Sweden

[c] Department of Electrical and Computer Engineering, The University of Dubrovnik, Ćira Carića 4, 20000 Dubrovnik, Croatia

ARTICLE INFO

Article history:
Received 29 November 2014
Received in revised form
26 August 2016
Accepted 28 February 2017

Keywords:
Networked control systems
Markov chain
Error state
State-dependent scheduling
Shared communication resource

ABSTRACT

In this work, we address the problem of event-based data scheduling for multiple heterogeneous LTI control loops over a shared resource-constrained communication network. We introduce a novel bi-character scheduling scheme, which dynamically prioritizes the channel access at each time-step according to an error-dependent priority measure. Given local error thresholds for each control loop, the scheduling policy deterministically blocks the transmission from sub-systems with lower error values. The scheduler then allocates the limited communication resource probabilistically among the eligible sub-systems based on a prioritized measure. We prove stochastic stability of the networked control system under the proposed scheduler in terms of f-ergodicity of the overall network-induced error. Uniform analytical performance bounds are further derived for an average cost function comprised of a quadratic error term and transmission penalty. The simulation results show that our approach results in a significant reduction of the aggregate network-induced error variance compared to the conventional scheduling protocols.

1. Introduction

Traditional digital control systems are typically associated with time-triggered control schemes and periodic sampling. The introduction of communication networks for data transmission between distributed entities in large-scale systems spurs the design of more advanced sampling strategies that result in more efficient utilization of resources. However, control over shared communication resources imposes several design challenges due to bandwidth limitations, congestion, collisions, delays and dropouts (Hespanha, Naghshtabrizi, & Xu, 2007). Many recent results (Åström & Bernhardsson, 2002; Dimarogonas & Johansson, 2009) suggest that it is often more beneficial to sample upon the occurrence of specific events, rather than after a fixed period of time elapses, especially when dealing with scarce resources.

The design of scheduling rules with periodic and aperiodic information updates is an active field of research (Lunze & Lehmann, 2010; Mamduhi, Molin, & Hirche, 2014; Molin & Hirche, 2014a,b; Tabuada, 2007; Walsh, Ye, & Bushnell, 2002; Wang & Lemmon, 2011). It is shown that event-triggered schemes often outperform time-triggered laws in terms of resource consumption while preserving the same level of control performance (Lunze & Lehmann, 2010; Molin & Hirche, 2014a; Tabuada, 2007; Wang & Lemmon, 2011). The efficiency of the event-based approaches in multi-loop NCSs, where multiple sub-systems compete for the communication resource, is even more evident (Cervin & Henningsson, 2008; Mamduhi et al., 2014; Molin & Hirche, 2014a,b). Try-Once-Discard (TOD) is a basic deterministic event-based scheduling law which awards the channel access to the system with the largest estimation error and discards the remaining transmission requests (Walsh et al., 2002). Stability criteria for such systems are based on the Maximal Allowable Transfer Intervals (MATI) (Nesic & Teel, 2004; Walsh et al., 2002). Approaches investigating stochastic stability of NCSs under event-based rules are presented in Donkers, Heemels, Bernardini, Bemporad, and Shneer (2012), Mamduhi et al. (2014) and Tabbara and Nesic (2008). Deterministic scheduling policies usually render improved performance in comparison with randomized ones as they award the channel to systems with the highest priority. However, they often lack scalability and flexibility in dealing with channel imperfections and might not be

☆ The material in this paper was partially presented at the 21st International Symposium on Mathematical Theory of Networks and Systems (MTNS), July 7–11, 2014, Groningen, The Netherlands. This paper was recommended for publication in revised form by Associate Editor Tamas Keviczky under the direction of Editor Christos G. Cassandras.

E-mail addresses: mh.mamduhi@tum.de (M.H. Mamduhi), adammol@kth.se (A. Molin), domagoj.tolic@fer.hr (D. Tolić), hirche@tum.de (S. Hirche).

[1] Fax: +49 89 289 25724.

http://dx.doi.org/10.1016/j.automatica.2017.03.005
0005-1098/

convenient for practical realizations (Christmann, Gotzhein, Siegmund, & Wirth, 2014). The majority of works, with notable exceptions in Blind and Allgöwer (2011), Cervin and Henningsson (2008), Mamduhi et al. (2014), Molin and Hirche (2014a) and Ramesh, Sandberg, and Johansson (2012), consider event-based scheduling policies for single-loop NCSs. Results on stability of multi-loop NCSs with event-based scheduling rules are found in Mamduhi et al. (2014), Molin and Hirche (2014a) and Ramesh et al. (2012).

Scheduling mechanisms can be realized in a centralized or distributed fashion. Time division multiple access (TDMA), and code division multiple access (CDMA) are two common centralized protocols often preferred in small and medium-size networks. They offer collision-free and precise channel scheduling with higher throughput, while they consume less energy compared to e.g. CSMA-CA policy, where each node senses the channel permanently (Shunyuan, Korakis, & Panwar, 2009). Furthermore, bandwidth arbitration is facilitated as they can prioritize channel access. However, they lack flexibility and scalability and are not suitable for large-scale networks due to their synchronous nature. Distributed approaches, represent easy-to-install, low-cost and scalable scheduling design suitable for NCSs with a large number of loops. However, collisions take place inevitably within distributed protocols and need to be handled with care in the NCS design. To exploit the advantages of both protocol types, hybrid designs are becoming evermore popular (Feng, German, & Dressler, 2010; Shunyuan et al., 2009; Zhou & Zhang, 2011).

We introduce a novel event-based bi-character scheduling rule for NCSs composed of multiple stochastic LTI control loops sharing a common communication medium. The proposed scheduler promises more efficient use of the scarce resource in comparison with conventional schemes. In our design, the scheduler deterministically precludes transmission requests of sub-systems with errors not exceeding pre-specified local thresholds. Afterwards, the channel is allocated probabilistically among sub-systems qualified for transmission, according to an online error-dependent priority measure. Since the local errors are driven by the Gaussian noise, transmissions occur randomly under an event-based rule. Consequently, by deterministically blocking the sub-systems with smaller local errors, the performance enhancement is attained. We show stochastic stability of the multi-loop NCSs in terms of f-ergodicity of the underlying error Markov chain. In addition, we derive analytical upper bounds for an average quadratic cost function.

In the remainder, Section 2 presents the problem of interest and provides necessary preliminaries. In Section 3, stability of NCSs under the proposed policy is studied. Performance analysis is then presented in Section 4. Finally, numerical results are illustrated in Section 5.

2. Problem statement and preliminaries

Consider a set of N heterogeneous LTI control loops coupled through a shared communication channel as depicted in Fig. 1. Each individual loop consists of a discrete time linear stochastic sub-system $\mathcal{P}_i$ and a controller $\mathcal{C}_i$, where the link from $\mathcal{P}_i$ to $\mathcal{C}_i$ is closed through the shared communication channel. A scheduling unit decides when a state vector $x_k^i \in \mathbb{R}^{n_i}$ at time-step k is to be scheduled for channel utilization, where n_i is the dimension of the ith sub-system. The LTI plant $\mathcal{P}_i$ is modeled by the following stochastic difference equation:

$$x_{k+1}^i = A_i x_k^i + B_i u_k^i + w_k^i, \tag{1}$$

where $w_k^i \sim \mathcal{N}(0, I)$ is i.i.d. at each time k, and for each sub-system i, while constant matrices $A_i \in \mathbb{R}^{n_i \times n_i}$ and $B_i \in \mathbb{R}^{n_i \times m_i}$ describe system and input matrices of sub-system i, respectively. Initial state x_0^i is randomly chosen from an arbitrary bounded-variance distribution. The overall network initial state x_0, together with the overall noise sequence w_k, generates a probability space $(\Omega, \mathcal{A}, \mathsf{P})$, where Ω is the set of all possible outcomes, $\mathcal{A}$ is a σ-algebra of events associated with probability P. The variable $\delta_k^i \in \{0, 1\}$ represents the scheduler's decision on whether a sub-system i transmits at a time-step k:

$$\delta_k^i = \begin{cases} 1, & x_k^i \text{ is sent through the channel} \\ 0, & x_k^i \text{ is blocked.} \end{cases}$$

We assume a loss-less channel, i.e. if a packet is transmitted, it will not be dropped. Data scheduling over lossy channels is investigated in Mamduhi, Tolic, and Hirche (2015b). It is assumed that the ith controller merely has local knowledge of A_i, B_i, and the distributions of process noise w_k^i and x_0^i, where the pair (A_i, B_i) is stabilizable. The control law γ^i is described by a measurable and causal mapping of past observations:

$$u_k^i = \gamma_k^i(Z_k^i) = -L_i \mathsf{E}\left[x_k^i | Z_k^i\right], \tag{2}$$

where $Z_k^i = \{x_0^i, \delta_0^i, \ldots, x_k^i, \delta_k^i\}$ is the ith controller observation history, and L_i is the feedback gain. A model-based estimator computes the state estimate if $\delta_k^i = 0$:

$$\mathsf{E}\left[x_k^i | Z_k^i\right] = (A_i - B_i L_i)\mathsf{E}\left[x_{k-1}^i | Z_{k-1}^i\right], \tag{3}$$

with $\mathsf{E}\left[x_0^i | Z_0^i\right] = 0$. The network-induced error $e_k^i \in \mathbb{R}^{n_i}$ is defined as $e_k^i \triangleq x_k^i - \mathsf{E}\left[x_k^i | Z_k^i\right]$. Employing (1)–(3), and the definition of the estimation error e_k^i, results in

$$x_{k+1}^i = (A_i - B_i L_i)\, x_k^i + \left(1 - \delta_k^i\right) B_i L_i e_k^i + w_k^i, \tag{4}$$

$$e_{k+1}^i = \left(1 - \delta_{k+1}^i\right) A_i e_k^i + w_k^i. \tag{5}$$

It follows from (4) that if the ith-loop is closed at time k, i.e. $\delta_k^i = 1$, the stabilizing gain L_i ensures the closed-loop matrix $(A_i - B_i L_i)$ is Hurwitz. Moreover, (5) indicates that the evolution of e_k^i is independent of the system state x_k^i and control input u_k^i. Define $[x_k^{i\mathsf{T}} e_k^{i\mathsf{T}}]^\mathsf{T}$ as the aggregate state of sub-system i. Stability of a closed-loop system i, however, does not imply convergence of the error state e_k^i. Hence, given a stable closed-loop matrix $(A_i - B_i L_i)$, showing convergence of e_k^i suffices to show stability of sub-system i with the aggregate state $[x_k^{i\mathsf{T}} e_k^{i\mathsf{T}}]^\mathsf{T}$. We show later that if A_i is unstable, then the ith loop needs to be closed "often enough" over an interval to ensure a converging error dynamics. This separation enables us to design the scheduler, which affects the error state e_k^i, independently from the control law u_k^i. To that end, we employ an emulation-based control strategy with the minimum required assumptions, i.e. stabilizing and linear control law, to ensure that the closed-loop systems are stable in the absence of capacity constraint.

In the scheduling design, the goal is to develop a new scheme which allocates the limited communication resources more efficiently resulting in an improved overall performance, while preserving stability of the stochastic NCS introduced in (1)–(5). We assume that the communication channel is subject to the capacity constraint such that not all sub-systems can simultaneously transmit. Consequently, some of ready-to-transmit data packets are blocked. Here, we introduce a novel error-dependent scheduling rule that dynamically prioritizes the channel access among the control loops competing for transmission. The scheduler decides on the priorities at each time-step according to all sub-system's latest error states. The following scheduling rule defines the probability of channel access for a sub-system i, at a time-step $k+1$,